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**Expert Systems Tools for
Hubble Space Telescope Observation Scheduling**

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Abstract

Construction of an efficient year-long observing program for the Hubble Space Telescope (HST) requires the ordering of tens of thousands of proposer-specified exposures on a timeline while satisfying numerous coupled constraints. Although manually optimized planning can be performed for short time periods, routine operations will clearly require that most of the planning be done by software. This paper discusses the utility of expert systems techniques for HST planning and scheduling and describes a plan for development of expert system tools which will augment the existing ground system. Additional capabilities provided by these tools will include graphics oriented plan evaluation, long-range analysis of the observation pool, analysis of optimal scheduling time intervals, constructing sequences of spacecraft activities which minimize operational overhead, and optimization of linkages between observations. Initial prototyping of a scheduler used the Automated Reasoning Tool (ART) running on a Texas Instruments Explorer Lisp workstation.

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1 Introduction

Scheduled for launch by the Shuttle in late 1988, the Hubble Space Telescope (HST) is an observatory of unprecedented capabilities. From a vantage above the bulk of the Earth's atmosphere, its scientific instruments will be able to observe farther and over a wider spectral range than any other telescope. During the design lifetime of 15 years, its complement of six scientific instruments should dramatically expand knowledge in essentially every area of astronomy. The Space Telescope Science Institute (STScI) is responsible for conducting the science operations of the HST, ranging from proposal solicitation, through planning and scheduling, realtime operations, data processing, archiving and user support [1].

Astronomers throughout the world will use the HST. A year's observing program for the observatory will consist of about 30,000 exposures on approximately 3000 celestial targets. In executing these exposures, a large number of constraints (scientific, hardware, orbital, thermal, etc.) must be satisfied. Additionally, it is crucial to maximize the scientific return by having an efficient schedule of observations. These factors make HST planning and scheduling a challenging problem.

Several aspects of expert systems are attractive for the construction of tools to aide scheduling, and the purpose of this paper is to describe a plan for the development of expert systems tools which would augment the existing ground system software. The next section presents an introduction to the HST planning and scheduling problem, including the major constraints and efficiency issues. Section 3 describes the tools and their planned development, including a justification of an expert systems approach.

2 The Problem of HST Planning and Scheduling

In order to use the HST, an astronomer submits a scientific observing proposal to the STScI. The proposal forms are "astronomer-friendly" in that they allow the proposer to describe what data must be obtained without becoming needlessly involved in the details of how the spacecraft and ground systems will implement the observations [2].

Based on the advice of a peer review committee of experts in a range of astronomical disciplines (the Time Allocation Committee), the Director of the STScI selects which proposals are to be awarded HST observing time [3]. Competition for HST time will be keen as the oversubscription ratio (number of submitted to accepted proposals) is expected to be at least three (typical for large, ground-based telescopes) and may approach a factor of ten. Of the 1000-2000 proposals submitted yearly, only about 200-300 will be accepted for execution.

While scientific merit is the most important selection criterion, the selection process must take into account various *resources* which are in limited supply, e.g. unocculted viewing time, power, communications, etc. In other words, a mixture of proposals which can actually be implemented by the spacecraft and ground systems must be chosen. It is important to note that *no scheduling* of proposals is performed at this stage: selection is based on estimates of the resources used by each proposal in comparison to the total estimated resources available in the coming year. Calculation of resource consumption by a proposal is uncertain at this stage since it is a function of both the time of observation and what other observations

are on the timeline (refer to the constraints listed in the next section). Resource usage estimates are calculated using an expert system described in [6]. Likewise, the total amount of resources available is uncertain since it depends on the activities to be scheduled and the possible carryover of high priority observations from the preceding cycle of observations. The decision process for proposal selection is aided by a natural language database query system [7].

The result of this selection process is a set of proposals to be executed in the coming year, and is therefore the input to the HST planning and scheduling process. Accepted proposals are called *programs* and are allocated to three scheduling priorities: high, medium and supplemental. Barring unforeseen technical difficulties, all high and medium programs will be executed, and together they account for approximately 70% of the estimated available observing time. The essential difference between high and medium is that greater emphasis is placed on completion of high priority observations (e.g. medium observations may be rescheduled to accommodate rescheduling of a high priority observation). The supplemental programs comprise a pool used to fill out the schedule; the choice of a particular supplemental program is likely to be based on operational constraints. Exposures in the supplemental pool oversubscribe the available time (and thus there is only a moderate probability that any particular supplemental program will actually be executed).

Following the selection process, proposers supply additional details required for scheduling and make any modifications imposed during selection (e.g. a decrease in the amount of observing time or number of targets). Next, the observing programs are transformed from the proposal format into the parameters required by the planning and scheduling system, effecting the translation from scientific objectives ("what") to hardware and software implementation ("how").

The processing of HST observing proposals is aided by the Proposal Entry Processor (PEP), which includes several systems utilizing AI techniques: Transformation from scientific proposal format into planning and scheduling system parameters is accomplished using an expert system [4], [5], as is the calculation of resource usage [6]. The selection process is supported by a natural language database query system [7]. Examination of observations for scientific duplication also makes use of an expert system [6].

At this point, the scheduling process begins with a pool of 200-300 programs encompassing tens of thousands of exposures on a few thousand targets. The overall goal of this process is to execute all the high and medium priority observations and as many supplemental observations as possible. Many observatories schedule by allocating blocks of time to observers, who then perform their own scheduling within that time (often scheduling in real time). HST scheduling takes a different approach: in the absence of scientific constraints to the contrary, exposures will be scheduled at times which increase the overall efficiency of the observatory. As a result, observations from any particular program may be spread over several months.

Science scheduling for HST is a two step process:

1. A time ordered sequence of exposures (called a *calendar* or *timeline*) is created from the program pool. The generation of timelines is currently envisioned to be an iterative process of increasing detail and density. High priority and time critical observations will be scheduled on a 6 month to 1 year timeline. Next, month long timelines will

be identified and populated with more observations, followed by week long timelines, etc.

2. Given a timeline, high level spacecraft instructions are attached to the activities on the timeline. The output of this process is a Science Mission Specification (SMS), and can be thought of as the "assembly language" which drives the HST. From the standpoint of the HST ground system, the purpose of the STScI is to produce the SMS.

To avoid confusion, it should be noted that for the HST domain, the terms "planning" and "scheduling" have switched meanings compared to their usual meanings in AI literature. HST "planning" refers to the process of scheduling activities on a timeline, while HST "scheduling" refers to the process of ordering spacecraft instructions to accomplish activities on the timeline. In practice, these terms are often used interchangeably.

The SMS is sent from the STScI to the Payload Operations Control Center (POCC) at Goddard Spaceflight Center where it is checked for errors and constraint violations which would affect the health or safety of HST or the instruments. From the SMS, the POCC prepares the actual binary command loads for the two onboard computers which control HST. Some iteration of the SMS occurs between the STScI and the POCC. The principal reason for this is the process of obtaining communications links. The POCC takes requests for Tracking and Data Relay Satellite (TDRS) links from the SMS and passes them onto the TDRS Network Control Center. Some links will not be available due to higher priority users (e.g. the Shuttle or other satellites). The POCC notifies the STScI of unobtainable links, and the timeline must be modified by the STScI, either by use of an onboard tape recorder or by rescheduling the observation.

2.1 Constraints and Operational Ground Rules

There are a number of considerations which influence the planning and scheduling process. These range from hard constraints, which if violated, may result in damage to the spacecraft, to operational ground rules which result in increased efficiency or flexibility.

Proposer specified constraints: In order to satisfy the scientific objectives of the observing program, astronomers can specify various relationships between exposures, for example:

- Time of observation: Although most exposures can be accomplished at any time, others must be accomplished within a certain time interval. Exposures with a narrow time window are referred to as *time critical*. Observations of periodic celestial phenomena (e.g. variable stars) may be constrained to certain phases.
- Precedence: before and after links between exposures
- Grouping: exposures which must be executed as a group, not necessarily in a particular order and without interruption by other activities.
- Priority and completion levels: In addition to the overall priority of a program (set by the Time Allocation Committee), a proposer may prioritize exposures within a proposal. Additionally, a level of completion may be specified, for example, 25% of

the targets must be observed for any to be useful, coverage of 50% of the targets will be optimal, but coverage of more than 75% may not significantly improve the results. This capability is especially important for supplemental priority and multi-year programs.

- **Conditionals and selects:** The HST observing proposal forms contain two constructs which allow the proposing astronomer considerable flexibility in specifying an observing program: "conditional" and "select". The first marks exposures which are contingent upon some condition, e.g. on the results obtained from some other exposure in the observing program or perhaps the results obtained from a ground based observation. Conditional exposures will not be scheduled until the proposer notifies the STScI that the condition has been satisfied. (This is in contrast to real time decisions which are handled by another mechanism). "Select" identifies alternative sets of exposures from which the proposer will select one or more for actual execution. As with conditional exposures, exposures contained in a select set will be placed on a timeline only after the proposer makes a final decision.
- **Dark time:** some exposures can only be executed when the HST is behind the Earth's shadow, shielded from the glare of the Sun.
- **Orientation:** certain observations require a particular orientation of HST in order to align a spectroscopic slit or polarization filter with features of a target. This factor is closely tied to power and thermal balance discussed below.

Realtime interactions: HST and the ground systems are designed to operate largely in a preplanned mode, e.g. the SMS must be complete three days before observations begin. However, the system is designed to support a certain level of realtime interaction. Examples include changing a filter in an instrument, a small angle maneuver for target acquisition or choosing among fully preplanned alternative observations. Realtime commands which would result in unplanned slews or major changes in instrument modes are not allowed. In general, realtime interaction places a large demand on spacecraft, communications and ground system resources, and its use must be carefully planned.

Orbital constraints: Many orbital factors exert a strong influence on the observing schedule. HST will occupy a low earth orbit (500 km), so a target on the orbital equator is occulted (blocked) by the Earth for about 39 minutes out of each 95 minute orbit. Long exposures will typically be implemented as a series of shorter exposures separated by Earth occultations. Targets within a few degrees of the orbital poles are not occulted by the earth, so this *continuous viewing zone* may be used for long observations which cannot be interrupted (if the target lies within this zone).

To avoid damage to the spacecraft and instruments, the HST cannot normally point to within 50 degrees of the Sun, nor can certain instruments view the bright Moon or Earth. In contrast, some instruments will use the bright Earth for calibration of the instrumental signature.

Another orbital factor is the South Atlantic Anomaly (SAA), a region where the Van Allen radiation belt dips into the orbit of HST. Noise induced by the charged particle radiation will prevent observations with most instrument modes in the SAA. However, one instrument (the High Speed Photometer) will be used to observe and map the extent of the SAA.

Power and thermal balance: Electrical power and a controlled distribution of temperature within the spacecraft are two closely related constraints. Power is generated on HST by a set of solar cells located on the "wings", and is stored in batteries. Instruments and other equipment can be damaged by extremes in heat or cold, and a proper thermal balance is accomplished by passive insulation, and active heating and cooling elements. In order to keep the solar cells pointed toward the Sun and to maintain the proper thermal balance, the V1-V3 plane of ST must normally be within 5 degrees of the Sun (V1 is the line of sight of the telescope, the V2 axis contains the solar arrays, while V3 is directed outward from the top of HST). Excursions as far as 30 degrees off this nominal roll are allowed as long as the batteries are allowed to properly recondition afterwards. Although most scientific observations will not require a particular orientation of HST relative to the sky (and thus a particular roll angle relative to the Sun), observations with certain instruments will (e.g. slit spectroscopy and polarimetry). As the solar cells and batteries age, their capacities will diminish and power constraints may become even more severe.

Guide stars: The HST uses Fine Guidance Sensors to lock onto two *guide stars* in order to compensate for long period drifts in the guidance system's gyroscopes. Although ample guide star pairs are expected to be available for most regions of the sky, certain regions will contain very few stars (and will restrict scheduling opportunities). Additional constraints arise when one pair of guide stars must serve two or more instruments (e.g. a target acquisition using a camera followed by an observations with a spectrograph). Guide star acquisition and lock requires several minutes, so guide star acquisitions should be minimized.

Scientific instruments: Cycling the scientific instruments from a standby to operate mode will require careful planning. Power constraints limit the number of instruments which can be collecting data simultaneously and the time to bring an instrument from standby to operate can be as long as 24 hours. Certain instruments and modes will require a set of calibration observations each time they are brought to operate mode.

Slews: Changing the orientation of HST to point to a new celestial target (called *slewing*), is a relatively slow operation. HST is only slightly faster than the minute hand on a watch, accomplishing a 90 degree slew in about 13 minutes. Note that optimization of slews alone is an NP-complete problem and is only a subset of the HST planning and scheduling problem.

Communications: All communications with HST (command uplinks and data readouts) is via the Tracking and Data Relay Satellite System (TDRS) which serves multiple users. As a consequence, HST planners must negotiate communications contacts two weeks in advance, and not all requested contacts may be available. Additionally, the HST orbit is low enough that during a portion of each orbit the Earth blocks one or both TDRS satellites. In each orbit, HST is limited to 20 minutes of high speed downlink contact. When a TDRS is not available for readout, onboard tape recorders can save science and engineering data for later playback. However the tape recorders have limited storage and lifetime, so their usage must be optimized.

Calibrations: As with any scientific instrument, HST instruments require calibration observations in order to produce meaningful scientific results, e.g. flat-field observations, dark count determination, wavelength calibrations. Although some calibrations will be routinely performed, others are dependent upon which exposures will actually be executed (e.g. high accuracy calibrations or calibration of seldom used modes). Some calibrations can be performed during slews (e.g. observations of internal light sources), while other will

require observations of standard reference targets. Most calibrations must be accomplished within a certain time of the science observation. Routine instrument calibration is the responsibility of the STScI.

Straylight and exposure times: Since many HST observations will be of extremely faint objects, contamination by straylight can be an important factor. Sources of straylight are time variable and include the Sun, Moon and Earth, and sunlight scattered by dust in the solar system (zodiacal light). Any of these sources may drastically increase the exposure time required to reach a specified signal to noise ratio.

Adjustment of exposure times: Given a fixed amount of straylight, in most instances, it is scientifically acceptable to adjust exposure times by small amounts (typically 10%) to fit within an available space (shorter or longer).

Schedule disruptions: Although HST operates largely in a preplanned mode, disruptions to the schedule will occur for a variety of reasons. The most welcome disruptions are *targets of opportunity*, which are rare, important astronomical phenomena requiring immediate attention (e.g. a supernova). The ground system should be able to respond to targets of opportunity as often as once a month, and be able to begin observations within a few hours of notification. Other schedule disruptions will result from equipment failures, spacecraft anomalies or loss of communications contacts. These will occur with little or no advance warning. It is important to be able to build schedules which minimize the sensitivity to disruptions (perhaps placing the HST in a checkpoint state at periodic intervals) and to be able to re-plan or patch schedules rapidly.

Insight into the planning process: It is important that the STScI operations staff have an understanding of the planning process, even in the case of automatically generated schedules. This includes explanations of why a particular observation was scheduled at a particular time and why it cannot be scheduled at another time.

The above enumeration of the constraints should make it clear that there are numerous constraints which have complex interactions, and that the number of feasible alternative timelines is so enormous that human planners cannot reasonably evaluate even a few hundred within the time limitations imposed by HST operations.

2.2 Current Ground System

HST planning and scheduling utilizes the Science Operations Ground System (SOGS) Science Planning and Scheduling System (SPSS), which was developed by TRW, Inc.

Within SPSS, the proposal data is represented by the following data structure:

- An "Exposure" is a single instrument operation, usually resulting in the acquisition of a single data set, e.g. a camera frame or a spectrum.
- An "Alignment" is a set of exposures that can be taken without moving the telescope (usually a single instrument and a single target, sometimes multiple instruments and multiple targets).
- An "Observation Set" is a set of alignments that can be performed without affecting the guidance system (that is, without reacquiring guide stars).

- A "Scheduling Unit" is a set of observation sets and is the smallest schedulable entity. Scheduling units can draw observation sets from any proposal (within an observation set, all alignments and exposures must come from the same proposal).
- Scheduling units may be linked (via before/after time intervals).

Note that this representation imposes a certain structure on the observations, generating constraints in their own right.

The first step in using SPSS is to populate the scheduling unit hierarchy. For most proposals this is handled automatically by PEP Transformation. Special cases can be populated manually either using PEP or SPSS functions. Next, the planner creates a *candidate and calendar (C&C) list*. The calendar is a time interval to be populated, while the candidates are scheduling units available to be placed on the timeline. Planners can manually add or remove scheduling units (with constraint checking performed by SPSS). SPSS provides functions which, given a candidate, find the best time to schedule it, or given a time, find the best candidate for that time. ("Best" is evaluated by a cost function which takes into account factors such as scheduling priority and slew time). In addition to the manual planning capabilities, an automatic scheduler is under development. Based on a greedy algorithm, it will find the candidate which best fits the next time on the calendar.

Once a timeline is populated with activities (observations, instrument reconfigurations, slews, etc.), high level spacecraft instructions are attached to the activities and then an SMS is generated for transmission to the POCC.

As a result of preliminary operations and testing of SPSS and increased experience with the planning and scheduling problem, STScI staff have identified a number of enhancements needed to make effective use of HST. Performance of the system is a major concern. In the operational era it must be possible to generate a day's SMS in less than one day of effort, averaged over all aspects of planning and scheduling, staff and computer resources. Current performance falls significantly short of this goal. Automation of labor-intensive and routine tasks will clearly benefit performance.

Currently there exist no tools to help planners in matching candidate scheduling units with calendars. Given the large pool of programs, tools are needed to select candidates from the pool which fit a specific calendar and to select calendars which would be appropriate for a specific program (or portion of a program).

Scheduling units must be created before they can be placed on a timeline, including the sequencing of individual exposures and spacecraft activities. Currently, SPSS places the activities on a calendar in the order specified with no attempt at re-ordering exposures to better fit the orbital events at that time (e.g. occultation, day/night, etc.). Such a fixed sequence will be non-optimal in all but the most fortuitous of circumstances and will therefore decrease the efficiency of HST. The current system does allow the planner to iteratively "hand craft" a scheduling unit and its components based on its place in a timeline, however this has an obvious impact on performance, and if the SU is ever rescheduled, the results of the effort are wasted.

Several of the proposer specified constraints can be implemented only by manual procedures, including proposer priority, completion levels, conditionals and selects. The current system also provides no assistance in determining what calibrations are required for a particular

timeline. Automatic placement of proper calibrations when scheduling observations, and avoidance of redundant calibrations is highly desirable.

Straylight and variable exposure times are also difficult to handle in the current system. Observations can be flagged as requiring orbital day or night execution and it is possible to make manual adjustment of the Sun, Moon and Earth avoidance limits, but a more automatic method with a finer degree of control is required. Expanding or trimming exposures by small amounts to fit within an available time slot can only be accommodated by a manual trial and error process.

3 Development of Tools for Planning and Scheduling

The previous section sketched the problem of HST scheduling and highlighted capabilities which are lacking from the current ground system. This section presents an approach to solving these problems using AI techniques.

Work towards ground system enhancement is directed along two lines: 1. increasing the performance, reliability, maintainability and functionality of existing SPSS software, and 2. creating new tools to augment the existing software. The former effort is largely directed at science instrument instruction management and SMS generation, while the latter is directed at scheduling and is the focus of the present paper. These two approaches will be carefully integrated to provide a coordinated effort for ground systems enhancement.

3.1 The Environment

Experience with Transformation and other rule-based software in PEP [4], [5], [6] has shown the advantages of a rule-based expert systems approach, especially with regard to rapid development, functionality, performance, adaptability of code to changing requirements and quick turnaround time for changes and enhancements. It is natural then that an expert system approach be utilized in the development of the proposed planning tools. It is important to note however, that expert systems are not a panacea for this problem. In particular, judicious use of procedural algorithms will be extremely useful in pruning alternatives before application of expert system rules.

OPS5, the computer language used for implementation of PEP rule-based software, is a language with which we have had great success in the past. However, prototypes in OPS5 along the lines of the proposed planning tools have revealed limitations in the language for such tasks, additionally, the Vax OPS5 environment provides no direct support for graphics output and lacks program development tools.

Preliminary investigations into planning tools have shown that a powerful knowledge-based development system which supports *hypothetical reasoning*, a *combination of forward and backward chaining* rules, and *frame-based data representation* which incorporates inheritance is needed for such a task. In addition, strong support for *graphics-oriented* programmer and user interface is required.

Forward chaining inference systems are appropriate for problems where there are many equivalently acceptable solutions (as in Transformation, design problems, and planning

problems in general). Forward chaining rulebased systems are very strictly data-driven: given a starting state, conclusions are drawn, and actions taken. Backward chaining allows the program to reason from desirable consequences to the causes which produce them.

Frame-based representation is an extremely powerful method of representing relationships between data. Many of the important characteristics of planning data are relationships, for example, exposures related in time, position, or due to membership in a scheduling hierarchy. A frame can be used to define a class of data, and another frame to define a subclass or refinement of that data. Subclasses automatically inherit the representations of the parent classes, with additions or changes as specified by the programmer. For example, one class might define exposures. A subclass of exposures with the Wide Field/Planetary Camera (WFPC), would inherit all characteristics of exposures, with specialized characteristics of that camera (e.g. power requirements). A sub-subclass might define types of WFPC exposures (e.g. data collection or target acquisition) which would inherit characteristics of exposures, WFPC exposures, and add characteristics such as realtime link requirements. Such expressiveness obviously speeds development, and aids maintenance and enhancement.

Another important requirement is the ability for hypothetical reasoning. This creates an alternate "world view" which is different from an existing set of facts in one or more ways. Hypotheticals have an obvious and natural application to scheduling problems in that they allow the evaluation of the effects of scheduling a proposal at different times. Rules can be written which check hypotheticals for contradictions, constraint violations, and inefficiencies, and which then mark that state as not worth further consideration. This limits the effort used in searching unprofitable alternatives, without the need for backtracking. Rules can also reason across multiple hypothetical states of the program, optionally merging several such states if appropriate (e.g. combining two partial timelines).

A fully integrated graphics interface is important for two reasons: First to support a rapid development effort (graphical browsing of the rulebase as well as the tracing of the program state during execution), and second, to provide a product with a powerful user interface. Graphic objects on the screen can be mouse sensitive, and changes to the display can automatically affect the rulebase and/or working memory. Thus, the user can play out "what-if" scenarios, e.g. by moving observations around on the timeline and having the program continue from the new state of the timeline data.

Development of an environment with the above capabilities is clearly a large task, so our approach was to look towards commercial products. A detailed survey of the market identified two advanced expert system environments which are suitable for initial investigations: ART (Advanced Reasoning Tool) from Inference Corporation, and KEE (Knowledge Engineering Environment) from Intellicorp. We have obtained a license for ART and have begun prototyping the tools described below; KEE is not yet available to us. A Texas Instruments Explorer Lisp workstation is the host for the development and is networked via TCP/IP over Ethernet to the DEC Vax computers which host the PEP and SOGS systems.

3.2 The Approach

As a first step towards evaluating the utility of AI tools to augment the ground system, a graphical plan evaluation environment is being developed. It will provide the basic functions of placing an activity on a timeline and removing an activity from a timeline. Calculation

of scheduling constraints will be fully integrated into the plan evaluator, including display of scheduling windows and display of constraint violations which prevent activities from being placed at a selected time. (Although calculation of constraints and scheduling windows is an algorithmic problem, application of constraints will benefit from a frame-based representation. Additionally, these constraints will play an important role in pruning the problem search space before application of expert systems rules.) Due to the complexity of the problem, considerable effort will be placed on the user interface, e.g. activities will be mouse sensitive to allow display and editing of their parameters, and users will be able to zoom and pan on the timeline (see [9] for a description of a related system).

The graphical plan evaluator is an important tool for both the software developers and operations staff. It will aid in capturing the basic domain knowledge needed by the developers in determining high-level approaches to scheduling and it will also serve as a testbed to try different scheduling algorithms and heuristics. For operations staff, even a prototype plan evaluator which allows the ability to rapidly develop alternative schedules will aid in the development of schedules and operational procedures. In particular, the plan evaluator will be useful in development of long range plans and in the determination of calibration requirements.

Although STScI operations staff have many years experience with spacecraft scheduling, our understanding of the problems associated with HST is not yet complete. An important part of the development of these tools will be an approach which allows the continuing experience of the operations staff to be reflected in the tools development.

After the development of the plan evaluator, the tools will be extended to handle:

- evaluation of exposures to identify preferred execution times (including such factors as sensitivity to background light)
- evaluation of "clumping" exposures that should be scheduled together
- introduction of plan evaluation measures that can be used to compare alternative timelines for efficiency.

This extension will allow operations staff to aggregate exposures into Scheduling Units, and recommended times for execution.

As experienced is gained in the implementation and use of these tools, the emphasis of the work will focus on integration of the tools into the operational environment. This includes integration with PEP transformation and the P&S software and data structures, e.g. generation of SPSS data records and scheduling commands to place them on the C&C list at the appropriate times. The tools will also be extended to include a fully automatic mode, based on guidelines and heuristics discovered as a result of working with the interactive system.

To conclude this section, we describe an initial scheduler prototype which has already been implemented in ART. The prototype handled multiple constraints, including guide star acquisition, Earth, Moon and Sun occultations, SAA avoidance, variable slew times, instrument usage (including scheduling a transition from hold to operate), exposure precedence links and time critical exposures. The input exposures were taken from the Design Reference Mission ([10], a manual exercise in HST scheduling), and are therefore realistic set of

science operations. The prototype scheduled the DRM's first week of observations (total of 75 exposures) in 45 minutes. The prototype consisted of 19 ART rules, supported by 9 Lisp functions. (Calculation of the orbital events and target visibility windows was performed using a separate package of Fortran programs developed previously.) Development of the prototype took one person two weeks. This exercise clearly demonstrated the power of the expert systems approach for HST scheduling: development was rapid, the language is expressive and powerful and well suited to constraint checking and hypothetical reasoning.

4 Conclusions

In this paper we have described the problem of planning and scheduling science observations for the Hubble Space Telescope and how the numerous, coupled constraints make for a difficult problem. Several aspects of expert system development environments are attractive for the construction of tools which will augment existing ground system capabilities, including the rapid development cycle, adaptability of code to changing requirements and powerful methods for representing and reasoning with knowledge. Additional capabilities provided by these tools will include graphics oriented plan evaluation, long-range analysis of the observation pool, analysis of optimal scheduling time intervals, constructing sequences of spacecraft activities which minimize operational overhead, and optimization of linkages between observations. A plan for the development of enhancements was discussed and the results of initial prototyping was presented.

References

- [1] *SO-07 Science Operations Concept*, 1983, Space Telescope Science Institute, SCI 82012B
- [2] *Call for Proposals and Proposal Instructions*, 1985, Space Telescope Science Institute, STScI SC-02
- [3] *SO-05 Proposal Solicitation and Review*, 1985, Space Telescope Science Institute, STScI 85051A.
- [4] Rosenthal, D., Monger, P., Miller, G., and Johnston, M. 1986, "An Expert System for Ground Support of the Hubble Space Telescope", *Proceedings of the 1986 Conference on Artificial Intelligence Applications*, NASA Goddard Space Flight Center
- [5] Lindenmayer, K., Vick, S. and Rosenthal, D. 1987, "The Operational Phase of an Expert System for the Hubble Space Telescope Ground Support", *Proceedings of the 1987 Conference on Artificial Intelligence Applications*, NASA Goddard Space Flight Center
- [6] Jackson, R. 1987, "Expert Systems Built By The 'Expert': An Evaluation of OPS5", *Proceedings of the 1987 Conference on Artificial Intelligence Applications*, NASA Goddard Space Flight Center
- [7] Hornick, T., Cohen, W., and Miller, G. 1987, "A Natural Language Query System for Hubble Space Telescope Proposal Selection", *Proceedings of the 1987 Conference on Artificial Intelligence Applications*, NASA Goddard Space Flight Center

- [8] *SOGS Science Planning and Scheduling System (SPSS) Functional Requirements Specification, STE-17*, 1983, NASA Goddard Spaceflight Center.
- [9] Taylor, W. 1987, Ames Scheduler and Planner User Interface Manual, NASA Ames internal document
- [10] Sherrill, T.J. 1983, *Design Reference Mission*, Lockheed Missles and Space Corporation.

